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# Depleted $^{15}N$ carryover, leaching and uptake for three years of irrigated corn

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## Abstract

Deep percolation of nitrate can contribute to the deterioration of groundwater resources. Leaching of nitrate is a complex process affected by fertilizer and irrigation practices, efficiency of N use by the crop, and how the soil's water holding capacity and water transmission properties are affected by soil texture. Depleted $(^{15}NH_4)_2SO_4$ fertilizer at N rates of 0, 125, 250 and 375 kg $ha^{-1}$ was applied annually for 3 years to continuous corn grown within three different water regimes. This time period and the labeled N permitted an evaluation of N use efficiency by the crop and $NO_3$ leaching and carryover on a Weld silty clay loam, a fine-textured soil, typical of the "hardland" soils of the semi-arid Great Plains. Three water regimes, $W_1$ ($\sim$ 1.5 ET), $W_2$ ($\sim$ ET) and $W_3$ ($\sim$ 0.8 ET), were used. Beneath each plot within each water regime, Duke–Haise vacuum trough extractors were installed under undisturbed soil profiles at 1.22-m depth to measure weekly percolate and the $NO_3$ concentration in the percolate. The corn was harvested in the fall in the dent stage to measure the total above-ground biomass N uptake. Soil profiles (1.8 m) were sampled annually in the fall after crop harvest to determine $NO_3$-N in the soil or carryover.

Great variability was encountered in measuring the amount of extractor water and its $NO_3$ content under each water regime, which made estimates of $NO_3$ leaching losses unreliable. Also, the variability demonstrates formidable problems in quantifying percolation losses with vacuum trough extractors under undisturbed fine-textured soil profiles. With the highest N rate of 376 kg $ha^{-1}$ $yr^{-1}$ and within the water regime $W_1$, where leaching was expected to be greatest, only 1% of the cumulative labeled N applied was found in extractor waters and most movement of the labeled N into extractors occurred the third year. The 125-kg-$ha^{-1}$-$yr^{-1}$ fertilizer N rate significantly increased the crop yield over the unfertilized plots without increasing residual $NO_3$-N accumulation; whereas fertilizer N rates of > 125 kg $ha^{-1}$ $yr^{-1}$ did not appreciably increase plant yields over the 125-kg-$ha^{-1}$-N rate, but did appreciably increase residual $NO_3$.

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## 1. Introduction

Inadequate rainfall is the major factor constraining agricultural productivity in the semi-arid Central Great Plains, U.S.A., west of the 98th meridian in Kansas and Nebraska to the base of the Rocky Mountains in Colorado. Smith and Cassel (1991) indicate the mean annual precipitation in this region is $< 43$ cm, with $\sim 10\%$ of the total occurring as snow and with the mean monthly potential evapotranspiration exceeding precipitation from April to mid-October. In general, $NO_3$ leaching would not be expected to pose a problem under average conditions. Where groundwater is available, energy resources have made irrigation systems possible, especially the center-pivot sprinkler system. Irrigated crops receive large quantities of N fertilizers and irrigation increases the probability of $NO_3$ movement in and beyond the root zone.

Smith and Cassel (1991) have pointed out that the potential for nitrate leaching depends upon soil texture, as it affects the available water holding capacity (AWHC) and the soil permeability. Smika et al. (1977) and Hergert (1986) have shown that good management of irrigation water and applied N are extremely important to nitrate leaching for corn production on the highly permeable and low-AWHC irrigated sandy soils of the region. On a fine-textured Sharpsburg silty clay Herron et al. (1971) found modest to substantial corn yield responses to applied N at three moisture levels (no irrigation, limited irrigation and optimum irrigation). Also, they found the annual application of excessive amounts of N fertilizer caused $NO_3$ carryover in the soil profile.

The objectives of this study were to measure the effect of fertilizer N rate (labeled N) within water regimes on the leaching and carryover of $NO_3$ and recovery applied N on a fine-textured soil typical of the "hardland" soils of the Great Plains.

## 2. Methods

The site selected had been in a dryland wheat fallow sequence and is located on the U.S. Central Great Plains Field Station, Akron, Colorado. The soil (Weld silty clay loam) is a fine, montmorillonitic, mesic Aridic Paleustoll. The average thickness of the A horizon is 25–30 cm and slowly merges with a lime–carbonate layer 20 cm thick and then into the unaltered parent loess that extends down to $\sim$ 1.8-m-depth before merging into a sand–gravel layer. Some soil properties were determined using methods by Workman et al. (1988). The low-lime, clay loam topsoil has a saturated paste pH of 7.4; an electrical conductivity of 0.06 S $m^{-1}$; and an organic matter (OM) content of 20 g $kg^{-1}$ as measured by $K_2Cr_2O_7$ and concentrated $H_2SO_4$ oxidation. The high-lime, silty clay loam subsoil has a pH of 8.3; an electrical conductivity of 0.09 S $m^{-1}$; and an OM content of 6 g $kg^{-1}$.

The site ($53 \times 27$ m) is located near an irrigation well and an electric source, which provided electricity for the water pump, air compressor and separate vacuum pumps for the vacuum trough extractors under each water regime. Installation of the extractor under each plot required considerable excavation. In order to keep soil disturbance on the experimental site to a minimum, the 3 irrigation regimes ($14 \times 27$ m) were separated by 3-m alleys where pits were excavated and excavated soil was piled. Six fertility plots, each $6.1 \times 4.6$ m, on each side of the irrigation block were separated by a 1.5-m boarder. Vacuum trough extractors constructed following specifications of Duke and Haise (1973) were installed under each plot in the fall before the first cropping year. To avoid disturbance of the structured soils above the trough, which could seriously alter percolation rates, a hydraulic-powered boring machine mounted on an "A" frame was lowered into the pit and a horizontal pilot hole 3.04 m long was drilled at 1.22-m depth beneath each plot. A rectangular coring tube was pushed into the pilot hole to shape the cavity for the extractor trough. The extractor trough (152 cm long $\times$ 15 cm wide $\times$20 cm deep) was filled with subsoil then pushed into this hole beneath the root zone on top of a pneumatic pillow. The pillow was inflated to a constant pressure year around with the air compressor to press the soil within the trough into firm contact with the undisturbed soil above. After extractor installation, bore holes were repacked with subsoil and the pits filled. Phenyl mercuric acetate was added weekly to the extractor collection containers to inhibit biological growth in the extractor water. Vacuum for the extractor candles within each water regime was maintained from June through September as outlined by Duke and Haise (1973), and extracted water from each plot was collected weekly and its volume measured to give estimates of percolation. The $NO_3 + NO_2$ in a small aliquot of the weekly percolate was measured using a Technicon®,[1] Auto-Analyzer and cadmium reduction of $NO_3$ to $NO_2$ and the colorimetric determination of the $NO_2$ with N-(*1*-naphthyl ethylenediamine) dihydrochloride and sulfanilamide. Magnesium oxide was added to the remainder of the percolate and steam distilled for $NH_4$ determination. Then Devarda's alloy was added and the percolate steam distilled for $NO_3 + NO_2$. When a large volume of extractor water was encountered, the sample was slightly acidified and then concentrated to 100–125 mL on a steam bath before adding, MgO and steam distilling.

Throughout the year daily maximum temperatures, precipitation and class-A pan evaporation (May through October) were recorded at a weather station within 100 m of the site.

During the growing season the soil's volumetric moisture was measured weekly for each water regime with a neutron moisture meter. The amount of irrigation water ($W$) to apply weekly was calculated from prior weeks' data as follows:

$$W = \left[(\text{precipitation}) + W_p\right] - \left[(\text{percolation}) + (\text{soil water content in 1.2-m soil profile})\right]$$

where $W_p$ = irrigation water applied from prior week. Then three water regimes ($1.5W = W_1$, $W = W_2$ and $0.8W = W_3$) were established. A solid set sprinkler system was used to apply the irrigation water and dikes were established around the edges of each plot so no irrigation water would run off.

[1] The use of brand names and company identification does not imply endorsement by USDA, ARS over similar products but is listed only for the benefit of the reader.

The $^{15}N$-depleted $(NH_4)_2SO_4$ fertilizer treatments were 0, 125 (adequate), 251 and 376 (excessive) kg $ha^{-1}$ $yr^{-1}$ labeled N, were randomized within a water regime providing three replications of the N treatments. It was assumed that N rates of > 125 kg $ha^{-1}$ would be in excess of plant needs, resulting in considerable accumulation of $NO_3$ in the soil profiles. The site could then be turn back to dryland wheat which could then be use to determine scavenging of labeled residual fertilizer N over years by winter wheat (Porter et al., 1990). Irrigated corn yields on the station were ~7840 kg $ha^{-1}$ (125 bushels $ac^{-1}$). Assuming 1% of the soil organic N was mineralized yearly the top 30 cm of topsoil, which contain ~4020 kg $ha^{-1}$ total N, would provide ~40.2 kg $ha^{-1}$ $yr^{-1}$ N. Thus mineralized soil N plus the fertilizer N rate of 125 kg $ha^{-1}$ N would provide ~0.021-kg-$kg^{-1}$-N corn (1.18 lb N $bu^{-1}$ corn) which was assumed to be about adequate to achieve near-optimum crop yield. The labeled N was applied to the soil surface of the 12 plots within a water regime with a small drop type Scott® lawn spreader in two directions and immediately raked in. The same source of labeled fertilizer and the same treatment was applied to the same plot annually for 3 years in early May just before planting.

The corn was planted in 76.2-cm row width with 22.9-cm spacing between plants (population of 57,383 $ha^{-1}$) about May 10 and harvested about September 10 while still in the dent stage. Weeds were controlled with pre-emergence application of either Atrazine® or Bladex 80® (2.8 kg $ha^{-1}$) and some hand hoeing. An Iowa Coop single Cross Hybrid MR-4®, variety S20, lot No. 1A, was planted the first and second year, but that variety was unavailable the third year and we planted Hybrid Jax 177®, Jacques Seed Co., 7R Lot 57796.

Two 1.82-m rows of corn per plot were harvested to estimate yield and obtain samples for total N and isotope abundance analyses. After removal of all plant samples, all remaining above-ground corn biomass was removed with a ensilage chopper to simulate corn silage harvest. Mineralization of above-ground resides N was eliminated by this removal. The plant samples were separated into ears, leaves and stalks. The ear included husk, cob and kernel. The samples were dried at 65°C, weighed, and then sample parts were processed through a chopper. Sub-samples of the chopped materials were ground through a large Wiley® mill and then further ground to ~75 μm with a Pitchford® Model 3800 stainless-steel ball mill. Total N in the plant parts was determined by Kjeldahl digestion modified with salicylic acid–thiosulfate for $NO_3$ (Bremner, 1965). Ammonium recovered by steam distillation of Kjeldahl digests, percolation waters and KCl extracts of soil was oxidized to $N_2$ with LiOBr using the conversion apparatus of Porter and O'Deen (1977) and the $^{15}N$ abundance of the $N_2$ was determined on an AEI® MS-20 dual inlet isotope ratio mass spectrometer.

In the fall of the year after the removal of the corn crop, soil samples were taken with a hydraulic sampler to a depth of 1.82 m in 15.2-cm increments. The soil samples were dried at 65°C and extracted with 1 *M* KCl for determining $NO_3 + NO_2$ and $NH_4$ by automated Technicon® analyses. The KCl extracts were distilled with MgO to remove $NH_4$ and then with Devarda's alloy to reduce the $NO_3 + NO_2$ to $NH_4$ for isotopic analysis as mentioned above.

The data were analyzed statistically using general linear model (GLM) analyses of variance procedures from SAS (1988, 6.03 edition).

## 3. Results and discussion

### 3.1. Climatic and watering regimes

Throughout the study the majority of the rainfall occurred from March through August (Table 1). Rainfall was sparse for the months of September through February, so leaching during these months would not be expected to be a problem. The pan evaporation data illustrate that the third year was warmer in May and June, cooler in August and warmer in September than the two earlier years. It is possible that precipitation that occurred in April or May before vacuum was applied to the extractors might have produced some percolation that was not measured. This is especially true during the first year when considerable rainfall occurred in May.

The intent of the $W_1$ water regime rate was to provide excessive water that might cause some leaching; the $W_2$ rate was to maintain the soil's water content; and the $W_3$ water regime was to decrease the soil's water content as the growing season progressed.

The depth of the water in the 1.22-m profiles for each of the water regimes at the beginning of the growing season (first week of June) and toward the end of the growing season (last week of August) are given in Table 2 for each cropping year. The $W_1$ water regime depleted soil moisture slightly during the growing season (2–3 cm) the first two years and started the third year with 2 cm less water. Moisture depletion in the $W_2$ water regime was 4–5 cm in years 1 and 2 and started the third year with $\sim 4$ cm less water than the second year and during the third year lost an additional 2 cm of moisture. Moisture depletion in the $W_3$ water regime was 9–11 cm for years 1 and 2, started the third year with $\sim 4$ cm less moisture and then lost an additional 5 cm of water during the growing season. The third year a blanket application of irrigation water (3.8-cm depth) was applied in May to all of the water regimes (Table 1) before neutron access tubes were installed. When the neutron tubes were installed and moisture measurements made, all water regimes started the third year at a lower water content than for prior years.

### 3.2. Percolation and leached N

The climatic potential for leaching is virtually nonexistent in the semi-arid regions of the Great Plains region (Smith and Cassel, 1991), so we expected the $W_1$ irrigation regime to be the only regime to experience leaching. The lack of replications for water regimes makes a statistical comparisons between water regimes impossible. However, the extractors beneath plots within a water regime should have produced approximately the same amount of yearly percolation. The percolation values (Table 1) represent the mean for all extractors for that year within a water regime. As the soil dried out in the $W_3$ water regime, where the irrigation applications were less than consumptive water use, it became progressively more difficult to obtain any soil solution with the extractors as the season progressed. The amount of percolate extracted displayed considerable variability among replicates within a water regime. The analysis of variance (ANOVA) for percolation under water regime $W_1$ showed that years were not significantly different at the 5% level and the analysis had a C.V. of 56%. Years were not significant different

Table 1
Monthly data (in cm) for rainfall, class-A pan evaporation (May–October), water applied to each water regime (June–August), and means for extractor water collected for each water regime (June–September)

| Month | Year 1 | | | | Year 2 | | | | Year 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | rain | irrigation | percolation | pan evaporation | rain | irrigation | percolation | pan evaporation | rain | irrigation | percolation | pan evaporation |
| Jan. | 0.7 | | | | 0.5 | | | | 1.0 | | | |
| Feb. | 0.5 | | | | 0.7 | | | | 0 | | | |
| Mar. | 3.0 | | | | 1.4 | | | | 3.5 | | | |
| Apr. | 3.0 | | | | 3.9 | | | | 3.0 | | | |
| May | 15.4 | | | 21.3 | 6.5 | | | 24.2 | 10.5 | 3.8 | | 28.8 |
| Jun. | 5.6 | | | 25.8 | 1.8 | | | 24.6 | 4.0 | | | 31.4 |
| $W_1$ | | 10.9 | 0.5 | | | 22.3 | 0.1 | | | 25.7 | 0.6 | |
| $W_2$ | | 7.3 | 0.7 | | | 17.4 | 0.3 | | | 18.3 | 0.9 | |
| $W_3$ | | 5.9 | 0.3 | | | 14.5 | 0 | | | 14.7 | 0.5 | |
| Jul. | 7.2 | | | 33.8 | 3.4 | | | 35.9 | 3.2 | | | 35.7 |
| $W_1$ | | 24.6 | 1.1 | | | 30.1 | 1.2 | | | 29.5 | 0.3 | |
| $W_2$ | | 16.3 | 1.6 | | | 19.3 | 0.3 | | | 19.3 | 0.5 | |
| $W_3$ | | 12.9 | 0.4 | | | 14.6 | 0.1 | | | 16.0 | 0.1 | |
| Aug. | 3.0 | | | 32.1 | 3.2 | | | 32.4 | 2.1 | | | 25.9 |
| $W_1$ | | 43.9 | 1.3 | | | 31.6 | 1.2 | | | 24.8 | 1.5 | |
| $W_2$ | | 28.7 | 1.6 | | | 21.2 | 0.5 | | | 16.9 | 1.3 | |
| $W_3$ | | 22.9 | 0 | | | 14.3 | 0 | | | 12.3 | 0 | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sep. | 1.1 | | | 23.0 | 4.0 | | | 21.2 | 0.3 | | | 28.9 |
| $W_1$ | | | 0.8 | | | | 1.1 | | | | 0.4 | |
| $W_2$ | | | 1.7 | | | | 0.1 | | | | 0.4 | |
| $W_3$ | | | 0 | | | | 0 | | | | 0 | |
| Oct. | 0.1 | | | 18.2 | 0.6 | | | 19.6 | 0 | | | 18.3 |
| Nov. | 3.6 | | | | 0.4 | | | | 1.2 | | | |
| Dec. | 0.6 | | | | 0.1 | | | | 0.2 | | | |
| Total | 43.8 | | | 154.2 | 26.5 | | | 157.9 | 29.0 | | | 168.5 |
| Totals | | | | | | | | | | | | |
| $W_1$ | | 79.4 | 3.7 | | | 84.0 | 3.6 | | | 83.8 | 2.8 | |
| $W_2$ | | 52.3 | 5.6 | | | 57.9 | 1.2 | | | 58.3 | 3.1 | |
| $W_3$ | | 41.7 | 0.7 | | | 43.4 | 0.1 | | | 46.8 | 0.6 | |

Table 2
Depth (in cm) of water in 1.22-m soil profile for start of growing season (first week of June) and (last week of August) by crop year and water regime

| Crop year | 1 | | | 2 | | | 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| Irrigation block | $W_1$ | $W_2$ | $W_3$ | $W_1$ | $W_2$ | $W_3$ | $W_1$ | $W_2$ | $W_3$ |
| Jun. | 33.4 | 30.8 | 31.3 | 33.9 | 33.6 | 31.9 | 31.7 | 29.7 | 27.8 |
| Aug. | 31.4 | 25.0 | 20.2 | 30.8 | 29.5 | 22.7 | 31.3 | 27.8 | 22.9 |

for either the $W_2$ and $W_3$ regimes and C.V.'s were 86% and 110%, respectively. The extreme variability for extractor water within a water regime over years does not provide a basis for making reliable estimates of leaching losses. The variability in percolate obtained by vacuum trough extractors for undisturbed fine-textured soil profiles was similar to variability encountered by Broadbent and Carlton (1978) using porous ceramic probes installed at various depths in irrigation plots, especially where low levels of irrigation was applied.

The cumulative means for total $NO_3$-N and labeled $NO_3$-N in the extractor water for the various irrigation regimes and fertilizer treatments are given in (Table 3). Years was not significant nor was there any significant N rate by years interaction. In the $W_1$ water regime the leached $NO_3$-N at the 376-kg-ha$^{-1}$-labeled-N fertilizer rate was significant different from the other N rates. Like the extractor water great variability was encounter in measuring the $NO_3$ in extractor waters with C.V.'s of 74%, 129% and 240% for the irrigation regimes of $W_1$, $W_2$ and $W_3$, respectively. The highest cumulative $NO_3$-N in percolate was in the $W_1$ water regime. If it is assumed that all of the $NO_3$-N in percolate resulted from the fertilizer application then 2.2% of the 1128 kg fertilizer N applied over 3 years moved to the extractors. However, less than half of this $NO_3$ was labeled N. Only traces of labeled $NO_3$ were found in the extractor waters under the $W_1$ water regime the first two cropping seasons with the majority of the labeled $NO_3$-N being collected the third cropping season. Thus a considerable time lag is required for transporting surface-applied fertilizer N through a 1.22-m silty clay loam profile.

Table 3
Means (in kg ha$^{-1}$) for cumulative $NO_3$-N and labeled $NO_3$-N in extractor water by N rate and water regimes

| Cumulative N applied (kg ha$^{-1}$) | Irrigation regime | | | | | |
|---|---|---|---|---|---|---|
| | $W_1$ | | $W_2$ | | $W_3$ | |
| | $NO_3$-N | labeled $NO_3$-N | $NO_3$-N | labeled $NO_3$-N | $NO_3$-N | labeled $NO_3$-N |
| 0 | 1.4a | – | 1.2a | – | 4.0a | – |
| 375 | 2.6a | 0.2a | 5.1a | 0.5a | 0.9a | 0.0a |
| 753 | 3.2a | 0a | 8.8a | 1.2a | 0.8a | 0.1a |
| 1,128 | 24.5b | 11.5b | 8.1a | 3.8a | 7.4a | 4.7a |

Means with same letter are not significantly different, LSD (0.05).

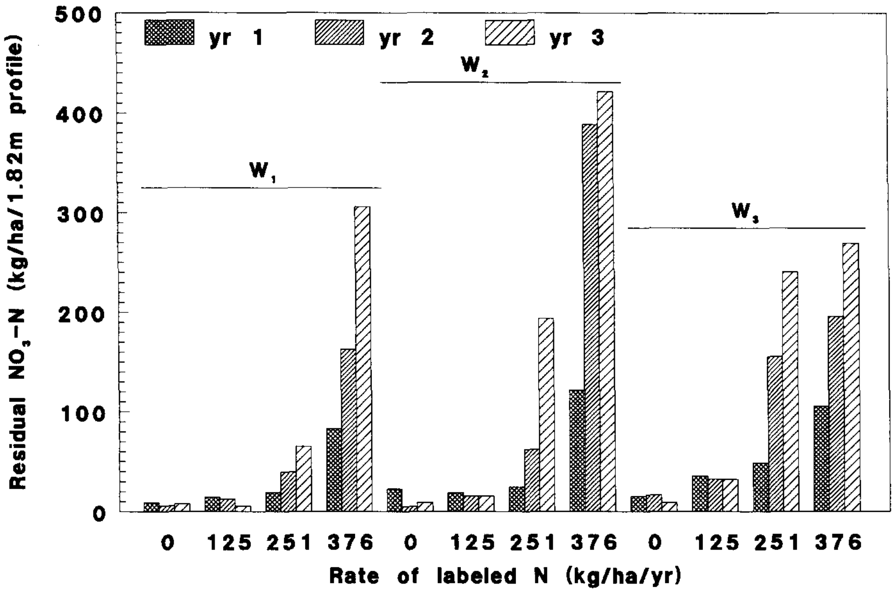


Fig. 1. Yearly residual $NO_3$-N in 1.82-m soil profile as affected by N rate and water regimes.

### 3.3. Residual $NO_3$-N

Residual $NO_3$ in 1.82-m soil profiles for each water regime increased with excessive N rates and with each additional cropping year (Fig. 1). The lowest fertilizer N rate, 125 kg ha$^{-1}$ N, had no affect on residual N in any year for all water regimes. Also, there was no difference for residual $NO_3$ between this N rate and the unfertilized (checks) for all water regimes. The 251-kg-ha$^{-1}$-N rate left significant residual $NO_3$ the third year in the $W_2$ water regime and in the second and third years in the $W_3$ water regime. The highest N rate, 376 kg ha$^{-1}$ N, left considerable residual $NO_3$ every year in all water regimes. These data support the concept that fertilizer N application rates required for near-maximum plant yield minimize accumulation of residual $NO_3$ in soils. Whereas, N rates above those required for near-maximum plant yields accumulate residual $NO_3$.

### 3.4. Above-ground corn biomass yield

Water regimes apparently had little effect on yields, even though difference between the water regimes cannot be tested. Within water regimes $W_1$ and $W_2$ N rate interacted with years (Table 4). If the third year was omitted from the analysis there was no interaction. The different corn hybrid and the drier soil conditions the third year may be responsible for the interaction. For each water regime each year there was a huge yield increase from the unfertilized to the lowest fertilizer rate. However, fertilizer N rates of $> 125$ kg ha$^{-1}$ yr$^{-1}$ only had slight effect on yield within each water regime.

Table 4
Total above-ground corn biomass yield by year as affected by N rates and water regimes

| N rate ($kg\ ha^{-1}$) | Yearly yields ($Mg\ ha^{-1}$) year 1 | year 2 | year 3 | mean |
|---|---|---|---|---|
| $W_1$: | | | | |
| 0 | 6.8 | 6.7 | 7.5 | 7.0 |
| 125 | 15.7 | 16.6 | 15.7 | 16.0 |
| 251 | 16.4 | 18.0 | 15.6 | 16.6 |
| 376 | 16.0 | 18.0 | 14.8 | 16.3 |
| LSD (0.05) | 1.8 | 2.3 | 2.2 | 1.6 |
| $W_2$: | | | | |
| 0 | 9.9 | 8.9 | 6.2 | 8.3 |
| 125 | 15.2 | 16.8 | 13.3 | 15.6 |
| 251 | 17.4 | 17.7 | 14.9 | 16.4 |
| 376 | 20.0 | 18.4 | 13.8 | 17.2 |
| LSD (0.05) | 2.9 | 3.6 | 3.0 | 2.2 |
| $W_3$: | | | | |
| 0 | 8.5 | 8.3 | 9.5 | 8.8 |
| 125 | 17.5 | 17.8 | 11.5 | 15.6 |
| 251 | 18.7 | 16.4 | 13.5 | 16.2 |
| 376 | 13.3 | 16.5 | 12.8 | 15.9 |
| LSD (0.05) | 3.9 | 3.2 | 6.4 | 1.7 |

ANOVA for each water regime

| Source | D.F. | $W_1$ | $W_2$ | $W_3$ |
|---|---|---|---|---|
| N rate | 2 | * * * | * * * | * * * |
| Year | 2 | * * | * * * | * * * |
| N rate × year | 4 | * | * | NS |
| C.V. (%) | | 5.9 | 9.6 | 17.9 |

D.F. = degrees of freedom; C.V. = coefficient of variation; * * *, * *, * = significant at 0.001, 0.01 and 0.05, respectively; NS = not significant.

### 3.5. Above-ground biomass N uptake

Increasing the fertilizer N rate increased the total N concentration of the above-ground corn biomass all years in all water regimes (Table 5). Within water regimes $W_1$ and $W_2$ fertilizer N rate interacted with years. At the highest N rate there was a declining N concentration the third year. In all years and for all water regimes the N concentration for the lowest fertilizer N rate 125 kg $ha^{-1}$ N was different from the unfertilized plots. Within water regimes $W_1$ and $W_2$ the N rate of 125 kg $ha^{-1}$ was different from the

Table 5
Yearly total N content of above-ground corn biomass as affected by N rate and water regimes

| N rate ($kg\ ha^{-1}$) | Total N content ($g\ kg^{-1}$) | | | |
|---|---|---|---|---|
| | year 1 | year 2 | year 3 | mean |
| $W_1$: | | | | |
| 0 | 5.9 | 5.1 | 4.9 | 5.2 |
| 125 | 8.5 | 10.3 | 8.9 | 9.2 |
| 251 | 12.8 | 13.5 | 11.7 | 12.6 |
| 376 | 13.8 | 13.6 | 12.7 | 13.4 |
| LSD (0.05) | 2.7 | 1.5 | 1.6 | 1.9 |
| $W_2$: | | | | |
| 0 | 5.5 | 5.5 | 4.9 | 5.3 |
| 125 | 7.7 | 10.4 | 9.1 | 9.1 |
| 251 | 11.2 | 13.4 | 12.9 | 12.5 |
| 376 | 15.6 | 13.7 | 13.6 | 14.3 |
| LSD (0.05) | 1.5 | 1.2 | 1.7 | 0.7 |
| $W_3$: | | | | |
| 0 | 6.9 | 5.6 | 6.7 | 6.4 |
| 125 | 10.0 | 11.9 | 11.1 | 11.0 |
| 251 | 12.1 | 14.2 | 12.7 | 13.0 |
| 376 | 14.5 | 14.2 | 13.6 | 14.1 |
| LSD (0.05) | 3.6 | 2.6 | 2.3 | 1.9 |

ANOVA for each water regime

| Source | $W_1$ | $W_2$ | $W_3$ |
|---|---|---|---|
| N rate | * * * | * * * | * * * |
| Year | * * * | NS | NS |
| N rate × year | * * | * * | NS |
| C.V. (%) | 5.1 | 7.7 | 11.6 |

C.V. = coefficient of variation; * * *, * * = significant at 0.001 and 0.01, respectively; NS = not significant.

higher N rates. And in water regime $W_3$ for the highest N rate of 376 kg $ha^{-1}$ the N rate of the first and third years was different from the 125-kg-$ha^{-1}$-N rate.

Within the $W_1$ and $W_2$ water regimes and for all years the total above- ground biomass uptake of total N at the 125-kg-$ha^{-1}$-N rate was different from that of the unfertilized plots. For these water regimes the 125-kg-$ha^{-1}$-N rate was different from the higher N rates of 251 and 376 kg $ha^{-1}$ (Table 6). In water regimes $W_1$ and $W_2$ N rates interacted with years for total N uptake. For these water regimes total N uptake increased during the second year and decreased the third year. For the $W_3$ water regime the total N uptake from unfertilized was different from the fertilized plots. In the first

Table 6
Yearly above-ground corn biomass total N uptake as affected by N rate and water regimes.

| N rate (kg ha$^{-1}$) | Total N uptake (kg ha$^{-1}$) | | | |
|---|---|---|---|---|
| | year 1 | year 2 | year 3 | mean |
| $W_1$: | | | | |
| 0 | 39.8 | 34.1 | 37.0 | 37.0 |
| 125 | 133.6 | 169.6 | 140.0 | 147.7 |
| 251 | 208.3 | 241.8 | 182.6 | 210.9 |
| 376 | 220.3 | 244.4 | 188.8 | 217.8 |
| LSD (0.05) | 43.3 | 17.6 | 35.7 | 28.8 |
| $W_2$: | | | | |
| 0 | 55.3 | 49.0 | 30.4 | 44.9 |
| 125 | 117.6 | 175.0 | 134.6 | 142.4 |
| 251 | 194.7 | 246.6 | 171.4 | 204.2 |
| 376 | 311.5 | 242.9 | 187.9 | 247.4 |
| LSD (0.05) | 34.8 | 55.2 | 39.5 | 25.4 |
| $W_3$: | | | | |
| 0 | 58.2 | 46.8 | 66.7 | 57.2 |
| 125 | 179.2 | 212.3 | 126.6 | 172.7 |
| 251 | 227.0 | 233.3 | 171.2 | 210.5 |
| 376 | 262.8 | 237.4 | 171.5 | 223.9 |
| LSD (0.05) | 83.1 | 63.8 | 69.3 | 25.4 |

ANOVA for each water regime

| Source | D.F. | $W_1$ | $W_2$ | $W_3$ |
|---|---|---|---|---|
| N rate | 2 | * * * | * * * | * * * |
| Year | 2 | * * * | * * * | * |
| N rate × year | 4 | * * | * * * | NS |
| C.V. (%) | | 7.1 | 13.1 | 23.5 |

D.F. = degrees of freedom; C.V. = coefficient of variation; * * *, * *, * = significant at 0.001, 0.01 and 0.05, respectively; NS = not significant.

year the 125-kg-ha$^{-1}$-N rate was different from the high fertilizer rates, but the next two years there was no difference between any fertilizer N rates.

The total N uptake = (labeled N uptake) + (indigenous soil N uptake), so the component parts of the total N uptake can be analyzed separately. Within water regimes $W_1$ and $W_2$ labeled N uptake increased enormously for N rates > 125 (Table 7). Since yields did not show such dramatic increases most of the increase is attributed to an increase in N content or luxury assimilation of labeled N as N rates increased. The significant (N rate) × (year) interaction was caused by an increased labeled N uptake the second year and a decrease the third year. Variability was greater in the $W_3$ water

Table 7
Yearly above-ground corn biomass labeled N uptake as affected by N rate and water regimes

| N rate ($kg\ ha^{-1}$) | Labeled N uptake ($kg\ ha^{-1}$) | | | |
|---|---|---|---|---|
| | year 1 | year 2 | year 3 | mean |
| $W_1$: | | | | |
| 0 | – | – | – | – |
| 125 | 67.1 | 98.1 | 76.7 | 80.6 |
| 251 | 135.8 | 186.7 | 130.7 | 151.5 |
| 376 | 162.4 | 187.7 | 145.5 | 164.7 |
| LSD (0.05) | 41.3 | 26.5 | 31.6 | 16.9 |
| $W_2$: | | | | |
| 0 | – | – | – | – |
| 125 | 53.9 | 105.1 | 67.2 | 75.4 |
| 251 | 128.4 | 180.0 | 127.0 | 145.1 |
| 376 | 230.1 | 180.8 | 146.1 | 185.7 |
| LSD (0.05) | 46.5 | 45.2 | 38.0 | 14.5 |
| $W_3$: | | | | |
| 0 | – | – | – | – |
| 125 | 77.1 | 138.0 | 70.9 | 95.3 |
| 251 | 139.2 | 160.1 | 116.2 | 138.5 |
| 376 | 192.0 | 168.2 | 129.5 | 163.2 |
| LSD (0.05) | 63.9 | 87.9 | 51.4 | 16.4 |

ANOVA for each water regime

| Source | D.F. | $W_1$ | $W_2$ | $W_3$ |
|---|---|---|---|---|
| N rate | 2 | * * * | * * * | * * * |
| Year | 2 | * * * | * * | * |
| N rate × year | 4 | * * | * * * | NS |
| C.V. (%) | | 10.7 | 17.2 | 29.1 |

D.F. = degrees of freedom; C.V. = coefficient of variation; * * *, * *, * = significant at 0.001, 0.01 and 0.05, respectively; NS = not significant.

regime than in the other water regimes. Within water regime $W_3$ there were no differences between the 125- and 251-kg-ha$^{-1}$-N rates, whereas the 125-kg-ha$^{-1}$-N rate was different from the 376-kg-ha$^{-1}$-N rate of the first and third years.

Within water regimes $W_1$ and $W_2$ added fertilizer N interacted with the indigenous soil N causing an increased uptake of indigenous soil N over the unamended soil (Table 8). As the fertilizer N rate increased above the 125-kg-ha$^{-1}$-N rate the uptake of indigenous soil N generally declined. Because of the high variability in the $W_3$ water regime this added N interaction could only be observed the second year.

### 3.6. Recovery of applied N

The recovery of fertilizer N [= (quantity of N in pool measured) × 100/(N applied)] can be determined by a number of methods (Hauck and Bremner, 1976). In this study the difference and isotope dilution methods will be compared to show how vastly different is the cumulatively N recovery when measured by these methods. In the isotope dilution method ($^{15}$N-depleted N in this study) the amount of fertilizer N in the pool is calculated from the atom % excess $^{15}$N times the total N in the pool of interest.

Table 8
Yearly above ground corn biomass uptake of indigenous soil N as affected by N rate and water regimes

| N rate (kg ha$^{-1}$) | Soil N uptake (kg ha$^{-1}$) | | | |
|---|---|---|---|---|
| | year 1 | year 2 | year 3 | mean |
| $W_1$: | | | | |
| 0 | 39.8 | 34.1 | 36.9 | 37.0 |
| 125 | 66.5 | 71.5 | 63.3 | 67.1 |
| 251 | 72.4 | 54.1 | 51.7 | 59.4 |
| 376 | 57.9 | 58.1 | 43.3 | 53.1 |
| LSD (0.05) | 18.2 | 13.8 | 14.1 | 12.9 |
| $W_2$: | | | | |
| 0 | 55.3 | 49.0 | 30.4 | 44.9 |
| 125 | 63.7 | 69.9 | 67.4 | 67.0 |
| 251 | 66.4 | 66.6 | 44.4 | 59.1 |
| 376 | 81.3 | 62.0 | 41.9 | 61.7 |
| LSD (0.05) | 18.7 | 24.2 | 13.8 | 15.4 |
| $W_3$: | | | | |
| 0 | 58.2 | 46.8 | 66.7 | 57.2 |
| 125 | 102.1 | 74.3 | 55.7 | 77.4 |
| 251 | 87.9 | 73.2 | 55.0 | 72.1 |
| 376 | 70.8 | 69.2 | 41.9 | 60.6 |
| LSD (0.05) | 47.8 | 19.2 | 44.3 | 20.0 |

ANOVA for each water regime

| Source | D.F. | $W_1$ | $W_2$ | $W_3$ |
|---|---|---|---|---|
| N rate | 2 | * * * | * * * | NS |
| Year | 2 | * * | * * * | * |
| N rate × year | 4 | * | * * | NS |
| C.V. (%) | | 10.0 | 13.4 | 28.9 |

D.F. = degrees of freedom; C.V. = coefficient of variation; * * *, * *, * = significant at 0.001, 0.01 and 0.05, respectively; NS = not significant.

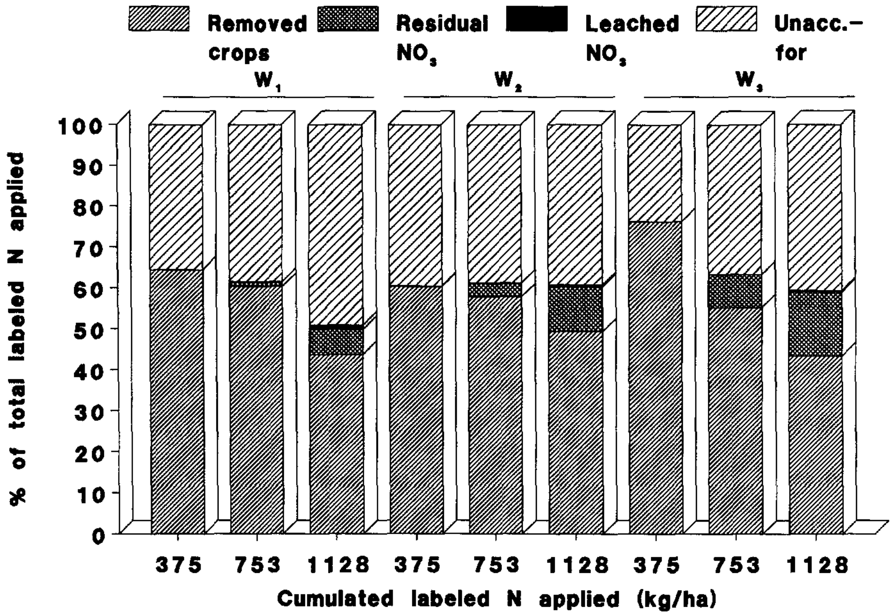


Fig. 2. Percentage of the total labeled N applied in N removed in crops, residual $NO_3$-N, leached $NO_3$-N, and unaccounted for N as affected by N rate and water regimes.

Unamended plots are utilized to determine the natural $^{15}N$ abundance of the pool. Users of the labeled N method assume that their interpretation of the labeled data is not confounded by biological or chemical displacement or pool substitution with unlabeled indigenous soil N (Jenkinson et al., 1985). In the difference method, the N pool in the fertilizer-treated plots is subtracted from unamended plots. Users of this method assume that unamended soils have N transformations, i.e. immobilization–mineralization, denitrification, chemical reactions and plant root exploration patterns similar to fertilizer-treated soils (Rao et al., 1992).

The recovery of cumulative labeled N in above-ground biomass, residual $NO_3$ and leached $NO_3$ are presented in Fig. 2. As mentioned above leaching of $NO_3$ was a minor proportion of the total labeled N applied. In water regime $W_1$ at the highest fertilizer N rate only 1.1% of the applied labeled N was found in extractor waters. In water regimes $W_2$ and $W_3$ the cumulative labeled residual $NO_3$ accounted for slightly more than 10% of the applied N. As the fertilizer N rate increased from 125 to 376 kg ha$^{-1}$ yr$^{-1}$ N the recovery of labeled N by the above-ground biomass decreased from 64% to 44%, from 60% to 49% and from 76% to 43% for the $W_1$, $W_2$ and $W_3$ water regimes, respectively. There are large amounts of labeled N unaccounted for in Fig. 2. Most of this unaccounted-for labeled N is in the soil organic N pool but because of the high degree of dilution of the depleted $^{15}N$ fertilizer by the much larger quantity of natural abundance organic N in the soil, an accurate measure of the labeled N in this soil

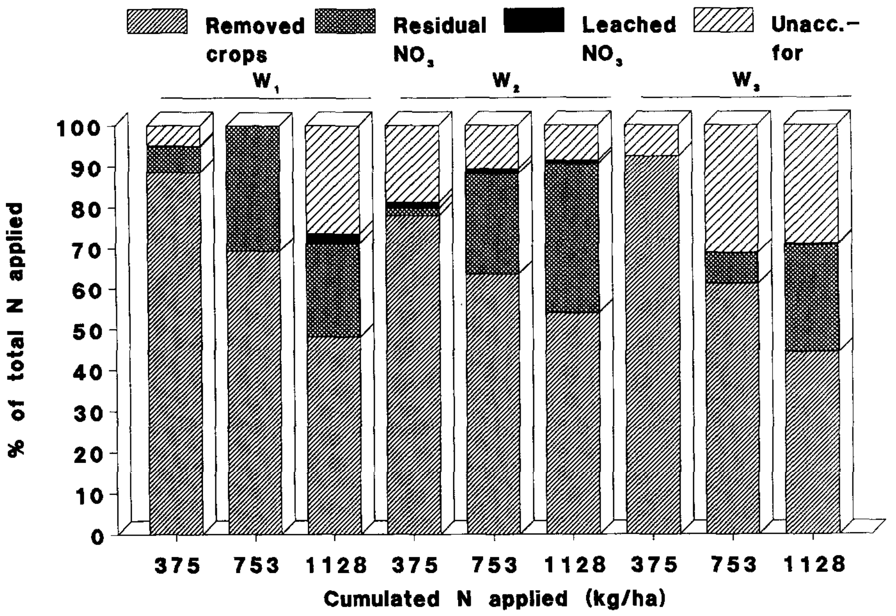


Fig. 3. Percentage of the total N applied as determined by the difference method (fertilized minus check) in N removed in crops, residual $NO_3$-N, leached $NO_3$-N, and unaccounted for N as affected by N rate and water regimes.

organic N pool was unattainable, and thus the unaccounted-for N pool was obtained by subtracting the other pools from the total N applied.

Determining the recovery of applied fertilizer N by the difference method (fertilized-unamended) shows a 16–25% increase over the isotopic dilution method for cumulative N recovery by the above-ground biomass at the 125-kg-$ha^{-1}$-$yr^{-1}$-N rate (Fig. 3). As fertilizer N rates increased from 125 to 376 kg $ha^{-1}$ $yr^{-1}$ N the cumulative N recovery decreased from 89% to 48%, from 78% to 54% and from 92% to 42% within the $W_1$, $W_2$ and $W_3$ water regimes, respectively. As the N rates increased the recovery of indigenous soil N decreased. For example, at the 125-kg-$ha^{-1}$-$yr^{-1}$-N rate within the $W_1$ water regime the cumulative recovery of fertilizer N in the above-ground biomass by the isotopic dilution method was 64% but by the difference method it was 88%, a 24% increase, whereas at the 376-kg-$ha^{-1}$-$yr^{-1}$ N rate the recovery was 44% by the isotopic dilution method and 48% by the difference method or only a 4% increase. Residual $NO_3$ accumulated only at N rates of $> 125$ kg $ha^{-1}$ $yr^{-1}$. The interesting question is, why at these higher N rates is half to two-thirds of this cumulative residual $NO_3$ non-labeled N? Is this positive ''added N interaction'' produced by isotopic displacement and pool substitution with the biomass or with a chemical reaction with some soil component, such as fixed ammonium? Whatever the explanation, it is apparent that considerably different recoveries are obtained depending upon what method is used to determine the recoveries.

## 4. Conclusions

(1) Great variability was encountered in measuring the amount of percolate and its $NO_3$ content which made estimates of leaching losses unreliable. This demonstrates formidable problems in quantifying percolation losses by vacuum trough extractors under undisturbed fine-textured soil profiles. Within water regime $W_1$ (1.5 ET) and at the highest N rate of 376 kg $ha^{-1}$ $yr^{-1}$ only 1% the total labeled $^{15}N$ applied was found in extractor waters. The majority of the labeled $NO_3$ in the percolation was collected in the third cropping season, illustrating that a considerable time lag is required for transporting surface-applied fertilizer $^{15}N$ through a 1.22-m silty clay loam profile.

(2) The data support the concept that fertilizer N application rates required for near-optimum plant yield minimize the accumulation of residual $NO_3$.

(3) There was a huge increase in above-ground biomass corn yields between unamended and those with the N rate of 125 kg $ha^{-1}$ $yr^{-1}$. However, N rates of $> 125$ kg $ha^{-1}$ $yr^{-1}$ caused only minor changes in yield within each water regime, but resulted in considerable $NO_3$ carryover.

(4) Recovery of applied fertilizer N by above-ground biomass within each water regime declined as N rate increased. Recoveries of applied N were considerably different depending upon the method used to determine the recoveries.

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